

Momentum Resolution Improvement Technique for Silicon Tracking Detectors using dE/dx

Stathes D. Paganis ¹

Columbia University, Nevis Laboratories,
P.O.Box 137, Irvington NY 10533, USA

Jaw-Luen Tang ²

Department of Physics,
National Central University, Chung-Li, Taiwan 320

Abstract

A technique for improving the momentum resolution for low momentum charged particles in few layer silicon based trackers is presented. The particle momenta are determined from the measured Landau dE/dx distribution and the Bethe-Bloch formula in the $1/\beta^2$ region. It is shown that a factor of two improvement of the momentum determination is achieved as compared to standard track fitting methods. This improvement is important in large scale heavy ion experiments which cover the low transverse momentum spectra using stand-alone silicon tracking devices with a few planes like the ones used in STAR at RHIC and ALICE at LHC.

PACS 29.40.Gx, 29.30.-h, 12.38.Mh

¹Corresponding author present address: DESY-F1, ZEUS Group Notkestrasse 85, HH 22603, Germany. e-mail address: paganis@nevis1.columbia.edu

²e-mail address: jawluen@bnl.gov

1 Introduction

Relativistic heavy ion experiments are performed in order to observe and prove the existence of a new form of matter, the Quark Gluon Plasma (QGP). A number of QGP observables rely on accurate measurement of the low transverse to the beam momentum (p_{\perp}) particle spectrum. Such measurement can provide an accurate interaction source size (as obtained from pion correlations), better temperature information, improved strange and multistrange particle reconstruction. For these reasons, large scale heavy ion experiments use vertex detectors and in particular silicon trackers, in order to deal with the high multiplicity of the collisions. STAR experiment at RHIC uses a 3 layer Silicon Vertex Tracker (SVT) and ALICE at LHC a 6 layer Inner Tracking System (ITS). For particle momenta below $200\text{MeV}/c$ there is significant increase of the multiple Coulomb scattering effect which results in a very poor momentum determination when standard track fitting methods are applied. Despite the very good position resolution of the silicon trackers ($10\text{-}20\text{ }\mu\text{m}$), the momentum resolution is $dp/p \simeq 25\%$ for $p = 100\text{MeV}$.

The purpose of this paper is to present an alternative method which can provide an improvement in the momentum determination by at least a factor of 2. The momentum is directly determined from the dE/dx measurement of every reconstructed track using the mean measured $\langle dE/dx \rangle$. The reasons for this dramatic improvement are: first, in the $1/\beta^2$ region for silicon the dE/dx distribution is narrow and can be fitted by a Gaussian with a small standard deviation, and second the slope of $\langle dE/dx \rangle(p)$ curve is large so that two neighboring distributions $\langle dE/dx \rangle(p_1)$, $\langle dE/dx \rangle(p_2)$ have a small overlap. Consequently one can use the mean $\langle dE/dx \rangle(p)$ of a track and the Bethe-Bloch curve to obtain a momentum with a relatively small error (around 10%).

The organization of the paper is as follows: in the first section we present an analytical proof of the method's validity, in the second section a simulation for a particular tracker is performed as an application of the method and finally the last section contains our conclusions.

2 Improving the momentum determination

In this section we show analytically using the well known Bethe-Bloch formula and the Landau dE/dx distribution for pions traversing a thin silicon layer, that the expected error in the the momentum determination of the incident pions is of order 10% for $p < 200\text{ MeV}$.

We start with the Bethe-Bloch formula [1]:

$$\frac{dE}{dx} = \frac{4\pi N e^4}{m c^2 \beta^2} z^2 \left(\ln \frac{2 m c^2 \beta^2 \gamma^2}{I} - \beta^2 \right) \quad (1)$$

where mc^2 is the rest energy of the electron, z the charge of the travelling particle, N the number density of electrons in the matter traversed and I the mean excitation energy of the atom. From (1) one can see that at low momenta the dE/dx falls fast like $1/\beta^2$ (the $1/\beta^2$ region), then goes through a minimum and rises very slowly for larger momenta. For a value of the momentum, dE/dx is distributed according to the Landau distribution.

A set of Landau distributions for pions going through $300 \mu m$ of silicon with a momentum in the range $50 MeV/c \geq p \geq 220 MeV/c$ is generated. Some of these distributions are shown in fig. 1. One can immediately see that the distributions are separated in the $1/\beta^2$ region and they get wider as the momentum decreases. It will be shown that the width of the distributions alone induces a relatively small error in the momentum determination of the beam. The overlap of the distributions though, makes a reliable momentum estimation impossible away from the $1/\beta^2$ region because a value of the dE/dx corresponds to a momentum range greater than 1 GeV wide. Thus it is only in the $1/\beta^2$ region where the overlap is minimum that we can apply our method. In fig. 2 we show the momentum error induced by the Landau distributions alone (i.e. errors due to overlap were not included). For a particular momentum the momentum error was determined as follows:

- the dE/dx was mapped to a momentum using the Bethe-Bloch formula (1). A momentum distribution was created about the original pion momentum.
- We obtained the distribution of the ratio $(p_{mapped} - p_{actual})/p_{actual}$ and fitted assuming it follows the Gaussian distribution.
- The momentum error plotted in fig. 2 is the standard deviation of the fit:

$$dp/p = \sigma((p_{mapped} - p_{actual})/p_{actual}) = \sigma(\Delta p/p) \quad (2)$$

We will call (2) the momentum resolution which is an index of the accuracy of the particle momentum determination.

In fig. 2 we see that the momentum resolution ranges from 6 to 14% in the interesting momentum region. The error bars come from the uncertainty that enters our calculation due to the fit. As we already mentioned the Landau distributions overlap for close enough momenta even in the $1/\beta^2$ region but no significant overlap occurs for distributions with momenta larger than one standard deviation of (2). As a result the momentum resolution in the $1/\beta^2$ region is $\simeq 10\%$. In this momentum region the momentum resolution obtained from standard fitting techniques is dominated by the multiple Coulomb scattering and is of order 20 – 25% or higher [2],[6], for a few layer Silicon based tracking detectors.

The above result comprises the central point of this paper: for few layer silicon based detectors with good hit energy loss dE reconstruction efficiency, the momentum is more accurately determined from the dE/dx distribution in the low p_{\perp} region ($1/\beta^2$ region of the dE/dx plot) than from standard fitting methods.

3 Simulations and Results

In this section our technique is applied on the STAR-SVT [3]. This detector consists of three concentric cylindrical layers covered with silicon drift detectors of $300\mu\text{m}$ thickness. SVT is capable of performing stand-alone tracking using the x, y, z coordinates of the 3 hits that a charged particle leaves when it crosses the detector. The tracking efficiency (i.e. the percentage of triplets of hits which correspond to the actual tracks that crossed the detector) is about 90% for the low momentum region and for tracks that originate from the main collision vertex (primary tracks). These tracks (in the region below $p_{\perp} = 200 \text{ MeV}/c$) are mostly pions (90% – 95%). The momentum resolution dp/p of the SVT has been extensively studied [2] and the results show that the resolution is rather poor for $p_{\perp} < 200 \text{ MeV}/c$. For primary tracks the momentum resolution $dp/p \simeq 25\%$ while for secondary tracks $dp/p \geq 30\%$. These numbers are in agreement with estimates for a 3 layer tracking detector from analytical empirical formulae [6].

To apply our method in SVT we use the dE/dx information as follows:

1. We generate the pion dE/dx versus p band using simulations that are verified by experimental data. This is done by sending pions of known momentum through the detector and extracting their dE .
2. We obtain the Landau distributions $dE/dx(p)$ for various momenta using a $50 \text{ MeV}/c$ momentum step. Every point in these Landau distributions corresponds to the truncated average dE/dx of a track. By truncated we mean that the maximum dE of the three hits is rejected and that $dE/dx = \frac{dE/dx(1)+dE/dx(2)}{2}$. In this way the long tail of the Landau distribution is reduced generating a more Gaussian-like distribution.
3. The mean dE/dx for each Landau distribution is obtained by performing Gaussian fit (fig. 3).
4. After we collect a set of mean values for a range of momenta from $50 \text{ MeV}/c$ to $1 \text{ GeV}/c$, we fit them using a polynomial fit to obtain an analytical expression for the mean

$$\langle dE/dx \rangle(p) = \text{Polyn}(p). \quad (3)$$

This expression maps the measured $\langle dE/dx \rangle$ of a track to a momentum (fig. 3). After tracking and standard fitting (typically helix fit) have been performed, we replace the momentum of the tracks with $p \leq 200 \text{ MeV}/c$ with the momentum obtained from (3).

Fig. 4 shows the obtained momentum resolution for pions. In the momentum region below $200 \text{ MeV}/c$ one can see that the average momentum resolution is $dp/p \simeq 10 - 11\%$ while for momenta greater than $200 \text{ MeV}/c$ the resolution is

greater than 20% because the method cannot be applied there and the momentum was obtained from a helix fit.

We expect that our method will be really useful for this low momentum region that only the Silicon tracker can be used for tracking. Fig. 4 clearly demonstrates that in the low momentum region the method provides at least a factor of two improvement of the momentum resolution. In these simulations a perfect knowledge of the energy loss dE in the silicon was assumed. In reality the dE of each hit on a wafer carries a measurement error which finally affects the momentum correction. On the other hand silicon detectors are capable of a quite accurate measurement of the dE . Another problem is the tracking efficiency for low momentum tracks; when a hit does not belong to a track the corresponding dE measurement is wrong and this will affect the momentum correction. Our simulations include the tracking efficiency errors.

4 Conclusions

In this paper a new method for improving the momentum determination of low momentum particles in silicon trackers was presented. The method was applied to a heavy ion experiment detector and an improvement of the momentum resolution by more than a factor of two was found. The method can be applied to any silicon detector that provides good dE information as in STAR-SVT at RHIC and ALICE at CERN. Knowledge of the pion momentum ($p_{\perp} < 200 MeV$) with an accuracy better than 15% can allow for interaction source size measurement using pion correlations, collision temperature studies, secondary soft pion reconstruction from V_0 decays and searches for pion excesses predicted in the QGP phase at low p_{\perp} .

References

- [1] Review of particle properties, Phys. Rev. D **50**, 1994, 1177;
- [2] S. Margetis, S. Paganis, STAR note 152, February 1994;
C. Pruneau et al., STAR note 162, May 1994.
- [3] John Harris et al, STAR Detector Conceptual Design Report, PUB-5347.
- [4] Peter G. Jones; STAR note 163, March 1994.
- [5] S. Paganis, S. Margetis; STAR note 126, September 1993.
- [6] R. Bock, H. Grote, D. Notz and M. Regler, (ed. by M. Regler).
Data Analysis Techniques in High Energy Physics Experiments.
Cambridge Univ. Press, Cambridge (UK), 1990.

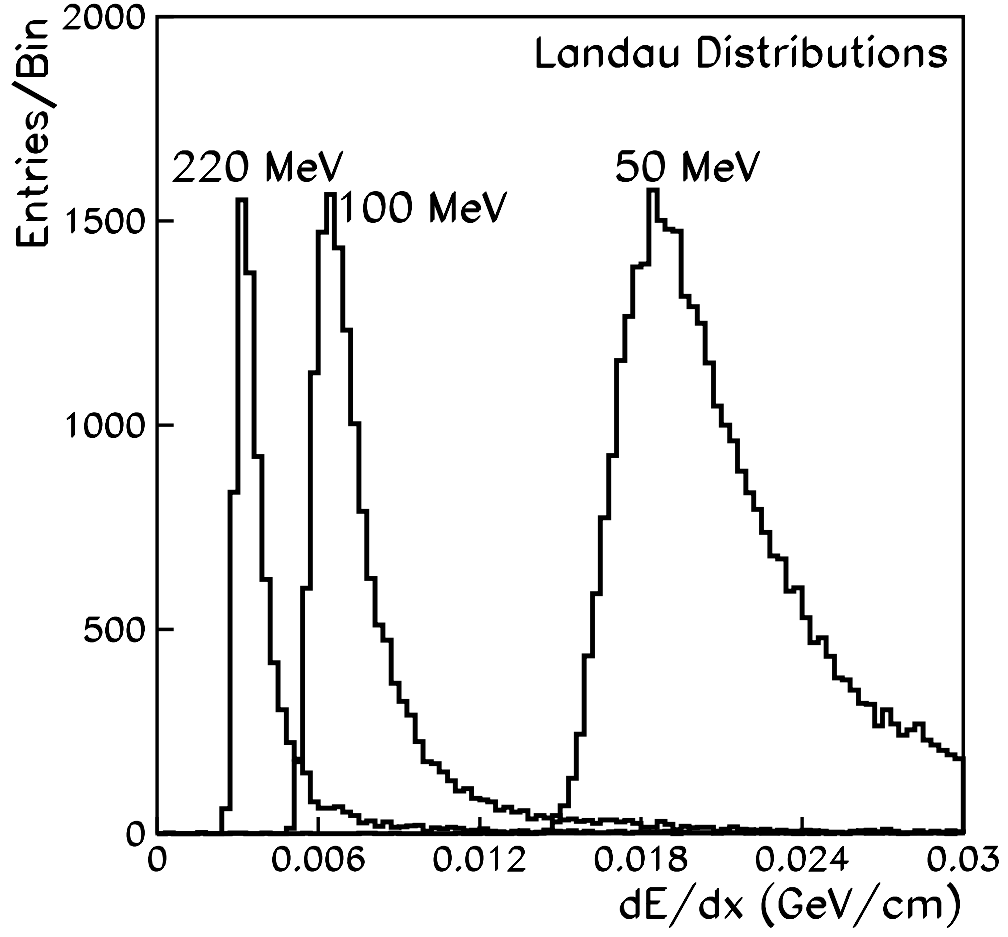


Figure 1: Landau $\langle dE/dx \rangle$ distributions for pions of momenta 220, 100 and 50 MeV going through $300\mu m$ of silicon.

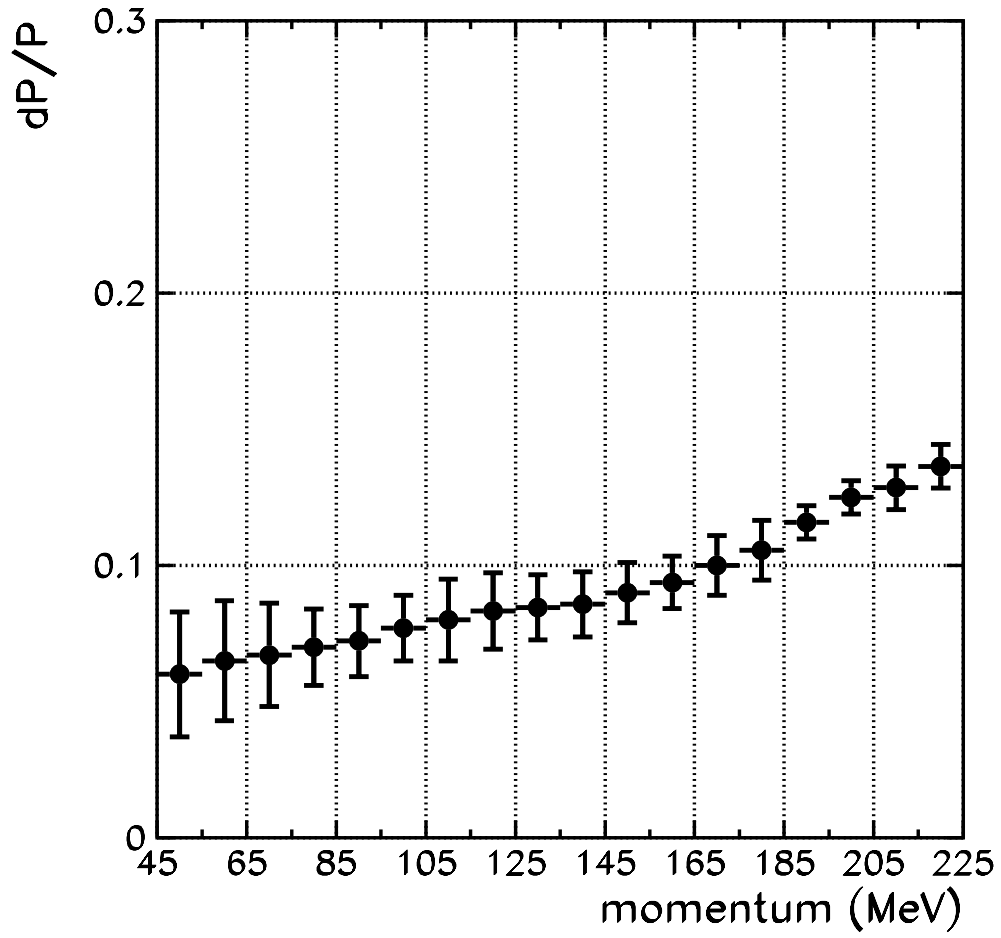


Figure 2: Theoretical error in momentum determination.

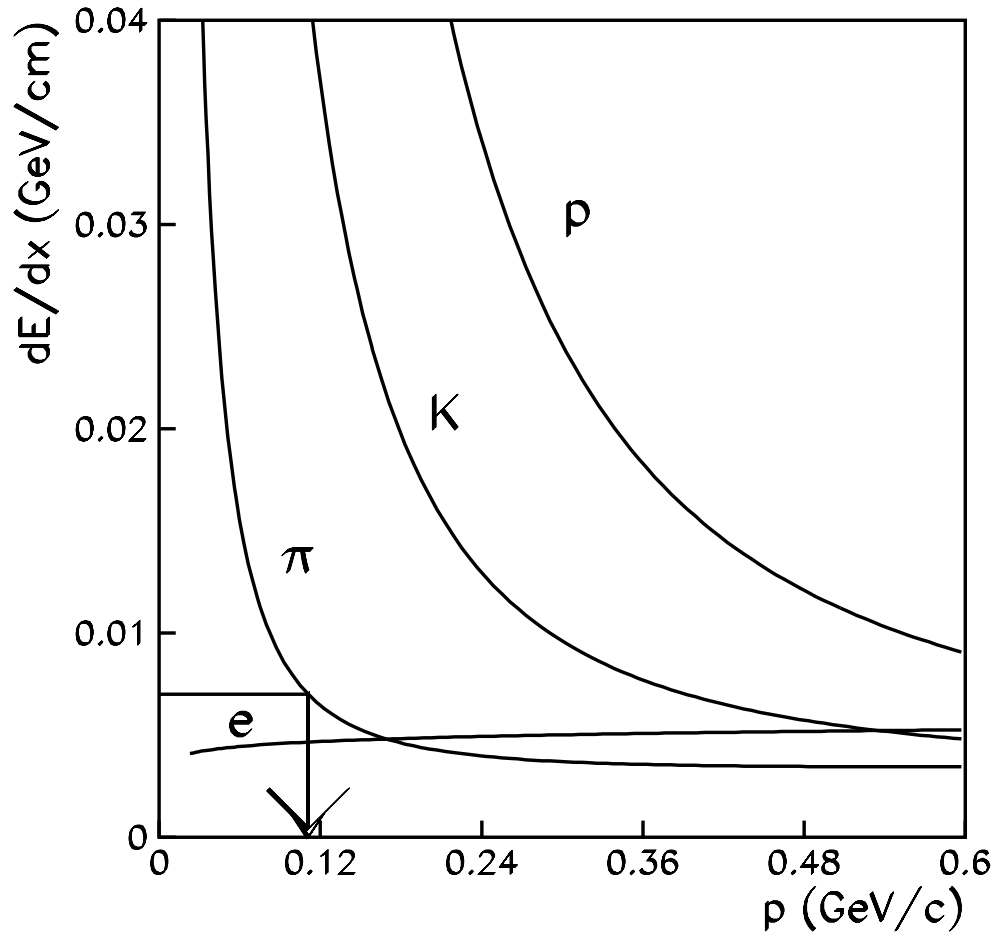


Figure 3: $\langle dE/dx \rangle$ as a function of momentum in STAR-SVT. For low momentum pions one can use the pion curve to extract the momentum from the measured dE/dx as shown.

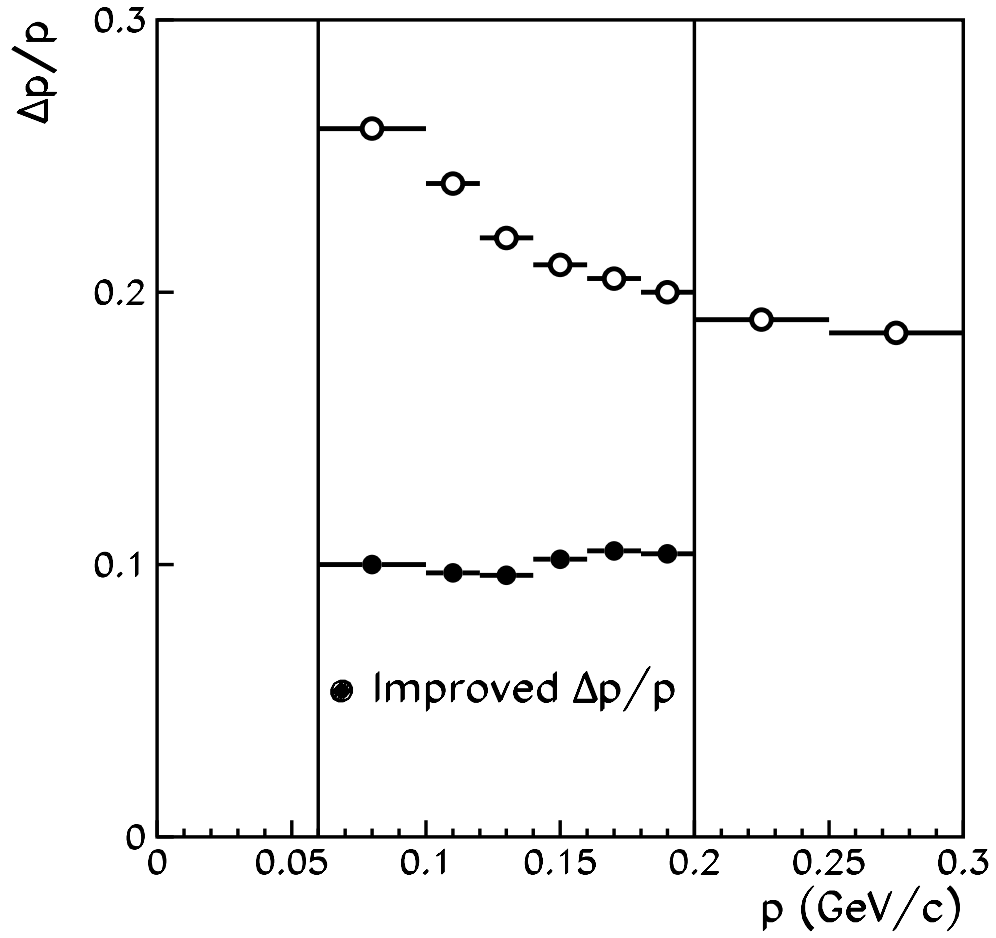


Figure 4: Momentum resolution improvement in the momentum range 50 – 200 MeV/c in STAR-SVT. Open circles denote the resolution obtained by a helix fit and filled circles the resolution when the momentum is extracted from the dE/dx information.